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PART REPAIRING USING A HYBRID MANUFACTURING SYSTEM (PREPRINT)

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PART REPAIRING USING A HYBRID MANUFACTURING SYSTEM

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ABSTRACT

At present, part remanufacturing technology is gaining more interest from the military and industries due to the benefits of cost reduction as well as time and energy savings. This paper presents the research on one main component of part remanufacturing technology, which is part repairing. Traditionally, part repairing is done in the repair department using welding processes. However, the limitations of the traditional welding process are becoming more and more noticeable when accuracy and reliability are required. Part repairing strategies have been developed utilizing a hybrid manufacturing system in which the laser-aided deposition and CNC cutting processes are integrated. Part repairing software is developed in order to facilitate the users. The system and the software elevate the repairing process to the next level, in which accuracy, reliability, and efficiency can be achieved. The concept of the repairing process is presented in this paper, and verification and experimental results are also discussed.

1. INTRODUCTION

Part repair technologies have been employed in many military and industrial applications such as torpedo shells, dies, molds, and turbine blades repair. Damage can occur during the operations or handlings. As shown in Figure 1, defects or damages can be categorized into four main types: crack, worn-out surface, corroded surface, and broken parts [1].

(a) (b)

Figure.1 Types of damages: (a) Crack (b) Worn-out or corroded surface

The size of the damage is used to classify each type of damage. The damage is classified as a crack if the width is tiny but the depth and the length of the damage are relatively large. Heat stress induces cracks in dies or molds and cracks in ship steel are caused by fatigue. If the width and length of the damage are large compared with the depth, then the damage is defined as a worn-out surface. Worn-out surfaces are typically seen in parts with movements such as shafts. Corroded surfaces usually occur on parts in extreme environments, such as inserts of molds and torpedo shells.

Common processes used in the part repair process are Gas Tungsten Arc Welding (GTAW) and Tungsten Inert Gag (TIG) welding. These traditional repair processes contain five basic steps [2]: (a) The damaged part is cleaned and the defects are identified, and then grease and other impurities are removed; (b) The damaged part is then pre-heated; (c) Filler is added via the welding process; (d) After welding, the part is then set aside to rest to relieve it from expansion due to the heat; and (e) Finally post-heat is applied to relieve the stress. However, there are some limitations of the welding process in part repair. The welding process cannot achieve high accuracy and reliability, and the deformation of the repaired part is usually large. Also the bonding between the filler and the damaged part is always poor. More importantly, some of the metal materials are not weldable.

To solve some of these problems, a cold repair process called Metalock process has been used, which avoids the stress due to the heat. Holes are drilled along the cracks and then tapped and filled with studs. The repaired pieces are not fused to a single piece. This method requires highly skilled technicians.

Laser welding process is another method that has been used in part repair. Laser welding process possesses advantages over the conventional welding process. For example, the heat-affected zone is relatively small compared with the welding processes. Thus, the deformation and stress are relatively small. Laser welding process can also be used with virtually any kind of material including unweldable materials. The time required for repairing is significantly reduced, and accuracy and repeatability can be achieved. However, this process limits itself to repairing cracks only due to the nature of the process.

The following section summarizes the applications of the part repair processes. In a work done by Camp and Bergan [3], torpedo parts were repaired using the laser-aided repair process. Motor shafts [4-5] and ship steel [6] were repaired using laser-aided repair processes. The corroded and worn-out dies and molds were fixed in the work done by Roy and Francoeur [7] as well as in the work done by Skzek and Lowney [8]. Laser welding was used to repair the corroded steam generator tubes in nuclear plants [9], and turbine blades were repaired using the laser cladding process [10-11]. The work done by Wang et al. criticized that the process planning for these repair processes is application specific [2].

2. REPAIR STRATEGIES

In this paper, the hybrid manufacturing system combines Layered Manufacturing and CNC machining. The resulting hybrid process can provide a greater build capability and better accuracy and surface finish by achieving the benefits of both processes [12-14]. Layered Manufacturing method used in this paper is Direct Metal Deposition (DMD) process, which utilizes a high-powered laser to melt metal powder layer-by-layer on the substrate to directly manufacture fully dense metal parts. Aiming at the main categories of defects shown in Figure 1, two repairing strategies using different toolpath generation patterns were advanced, which will be called feature replacement and surface patching later in the paper. As the name shows, feature replacement means the method of machining the damaged feature out and depositing back the repaired feature, and it is designed especially for repairing cracks and broken parts. In contrast, surface patching is only applicable for another two categories of defects: corroded or worn-out surfaces. These two strategies will be demonstrated in detail later. Meanwhile, the repair process planning software is developed to facilitate users on the VISUAL C++ programming platform, using ACIS as the modeling kernel and HOOPS as the graphics display engine.

<u>Feature Replacement Method</u>

In this strategy, the damaged feature is machined off and deposited back, and then surface machining brings the whole repairing process to the end. The process planning procedures are as follows: a) define the to-be-repaired feature, b) generate the contour offsetting machining toolpath to machine out the damaged feature, c) generate the contour offsetting depositing toolpath to deposit back the feature to the original, and d) post-process the toolpath data to get the CNC codes file for a specified hybrid manufacturing system. The contour offsetting has been studied extensively. Many approaches exist for constructing the offset paths for the 2-D contours. These methods can be categorized into three groups: pair-wise offset [15], pixel-based [16], and Voronoi approaches [13, 17-22]. Some of the earlier works reported that their algorithms can be successfully used with arbitrary shapes [15-16, 20-21]. In general, the offset curves can be defined using Minkowski operations described below.

<u>Minkowski Operations (Sum and Subtraction)</u>

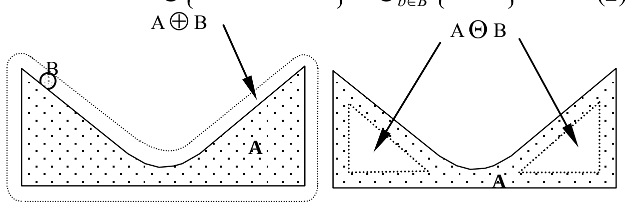
Minkowski operations have been used in the areas of image processing and robotics path planning. Minkowski Sum and Minkowski Subtraction are known as dilation and erosion, respectively, in the area of image processing. Let A and B be sets as shown in Figure 2. $A \oplus B$, the Minkowski

Sum of set A and set B, denotes the sum or the addition of the two sets. Minkowski Sum is defined as follows:

$$A \oplus B = \{a + b : a \in A \text{ and } b \in B\} \qquad (1)$$

It is common to write A+b instead of {a + b: a $\in$ A}. Thus, A $\oplus$ B can also be defined as follows:

$$A \oplus B = \bigcup \{A + b : b \in B\} = \bigcup_{b \in B} \{A + b\} \qquad (2)$$



(a) (b)

Figure.2 (a) Minkowski Sum A $\oplus$ B and (b) Minkowski Subtraction A Θ B

Similarly, the Minkowski Subtraction (A Θ B) is defined as fllows:

$$A \Theta B = \bigcap \{A + b : b \in B\} = \bigcap_{b \in B} \{A + b\} \qquad (3)$$

Interior, Closure, and Boundary Operations

Let X be a closed set (i.e. X = {x: x $\in$ X}). The interior of set X is the union of all open sets within X, denoted as int(X). Note that int(X) is necessarily an open set. The closure of set X, denoted as cl(X), is the intersection of all closed sets containing X, and cl(X) must be closed. The boundary of set X, denoted as ∂(X), is its closure minus its interior.

$$\partial(X) = cl(X) - \text{int}(X) \qquad (4)$$

Offset Paths

Let R be the target region in which the coverage paths are planned, and let T be the virtual tool shown as a planar disk in Figure 3. Also, at iteration *i*, let *Oi* be a set in which the distance from the contour to any points in the set is larger or equal to a fixed distance, *di* (*di* = *i* * *D,* where *D* = diameter of the tool or laser diameter - overlap). The boundary of set R as ∂(R) is the contour boundary of the target region.

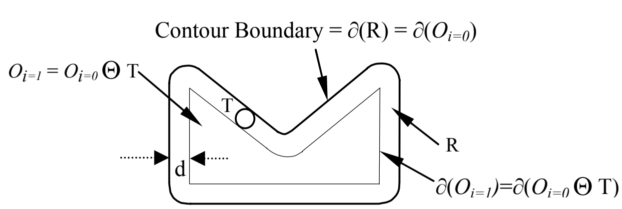


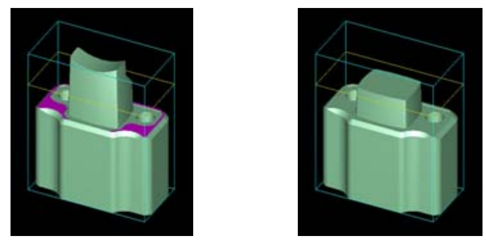
Figure.3 Relationship between the offset curve and Minkowski subtraction ($O_{i=0}\,\Theta$ T)

At iteration *i*, the set *Oi* is equivalent to Minkowski Subtraction of the set *Oi-1* and the tool area (*T*). The deposition path *∂(Oi)* is defined as:

$$\partial(O_i) = \partial(O_{i-1} \Theta T) = \partial(\bigcap_{t \in T} O_{i-1} + t) \qquad (5)$$

Path Generation

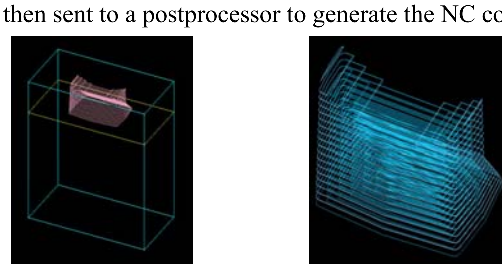
The following is a repair example to illustrate how this strategy works. Figure 4 shows the damaged part before defining the damaged feature and after the damaged feature is removed.



(a) (b)

Figure.4 (a) The entire cutting plane option and (b) the part after removing the damaged feature

The paths for deposition were generated automatically using the contour offsetting pattern in the software written in Visual C++. The results are shown in Figure 5. From the figure, the defined damaged feature was sliced, and the toolpath was generated for every slice. The deposition paths were then sent to a postprocessor to generate the NC codes.



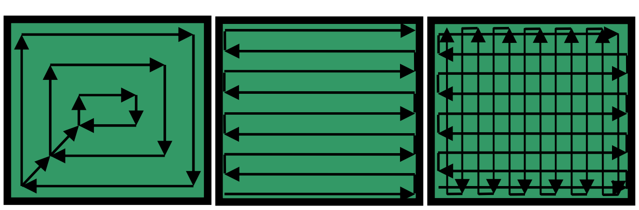
(a) (b)

Figure.5 (a) Slices and (b) Deposition paths (close up)

The drawback of the above repair strategy is that for worn-out or corroded surfaces, pre-machining is unnecessary. This implies that replacing the damaged feature is not the best strategy for finishing a repair job. Also, the contour offsetting toolpath pattern sometimes cannot guarantee the deposition quality because of the possibility of generating the porosity and bad surface evenness during deposition. Aiming at the above limitations, the surface patching method is investigated using the adaptive zigzag toolpath pattern especially for the worn-out or corroded surfaces in this paper. For a worn-out surface, the materials can be deposited on the damaged surface directly using the adaptive zigzag toolpath without pre-machining. The major difference between those two toolpath generation patterns will be demonstrated in detail in the later sections.

Surface Patching Method

Surface patching method is a process planning strategy especially for repairing worn-out and corroded surfaces by a hybrid manufacturing system. It uses the adaptive zigzag toolpath pattern for toolpath generation, which changes the raster direction in the connective layers compared with the traditional zigzag machining toolpath [23-24]. Figure 6 shows the difference among the contour offsetting pattern, the traditional zigzag toolpath pattern along a fixed direction, and the adaptive zigzag toolpath pattern for deposition along interlaced directions. As the figure demonstrates, the major difference between those two zigzag patterns is the travel direction. Instead of a fixed direction in Figure 6(b), the travel direction in Figure 6(c) keeps switching in every connective layer, e.g., the horizontal direction in the first layer, the vertical direction in the second layer, and then the horizontal direction in the third layer again and so on. The other difference is that the boundary of the surface needs to be traveled first in the adaptive zigzag pattern, and then the offsetting surface area (the offsetting distance is usually the size of the laser spot) is filled by an interlaced zigzag toolpath. The reason why the boundary of the original surface needs to be traveled first and then offset to get the target area for filling the toolpath is because the extra materials will not be deposited on the boundary and the boundary will not be over-deposited as to destroy the surface evenness. Apparently, this will reduce the chances of the occurrence of porosity. As far as the traveling direction is concerned, usually the two principle axes of the target area are considered to be the best choices.



(a) Contour offsetting (b) Zigzag (fixed direction) (c) Zigzag (interlaced direction)

Figure.6 Different toolpath generation patterns

Figure 7 demonstrates the adaptive zigzag toolpath generated by the process planning software for the connective two layers of the triangular target area. The distance between these two layers is the layer thickness depending on the different operation parameters in the hybrid manufacturing system. As shown, the target area is created by offsetting the original triangular surface. The toolpath for the bottom layer (Layer I) travels along the horizontal direction, while the traveling direction for the top layer (Layer II) is vertical with the previous travel direction (horizontal direction).

Figure 8 shows two deposition results of the same geometries obtained from two different toolpath patterns. In (a), the target geometry is filled by the contour offsetting pattern, and in (b) the toolpath pattern is the adaptive zigzag pattern discussed above. As shown in the figure, the surface evenness of (b) is much better than the surface evenness of (a). Also, Figure 8(a) shows that there is a hump in the middle of the target area, which often happens when depositing by the contour offsetting pattern.

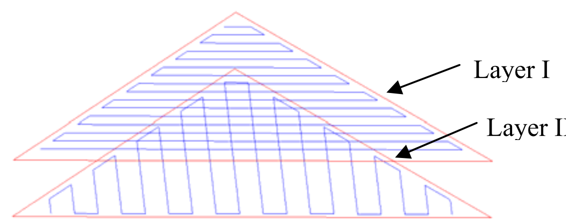


Figure.7 Interlaced zigzag toolpath in two connective layers

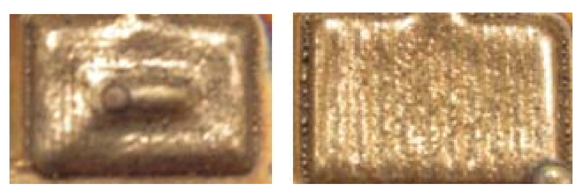


Figure.8 Depositions obtained from two different toolpath patterns

Another advantage of this toolpath pattern is its feasibility and generality for a curved surface, which means it can follow the surface contour and act like the meshing grid of the curved surface. From another point of view, the adaptive zigzag toolpath can even be considered as the parametric curve expressions along two major axes that completely retain the surface contour information. Figure 9 shows the adaptive surface patching zigzag toolpath for the curved face in both 2-D and 3-D modes generated by the repairing process planning software.

It can be seen that 2-D surface patch zigzag toolpath is generated by filling the projected area of the target face on an X-Y plane, and it actually loses most information about the target curved surface. Being different from the 2-D surface patch, the 3-D surface patch keeps almost all the feature information of the target surface and definitely will result in a better deposition quality in most situations. Weather to use the 3-D surface patch actually depends on the curvature of the curved surface. Experimental results prove that the deposition quality almost stays the same when using either a 2-D or 3-D surface patch if the curvature is not very high. However, for high curvature, deposition using the 2-D surface path is even unsuccessful and the 3-D surface patch undoubtedly is the optimal strategy.

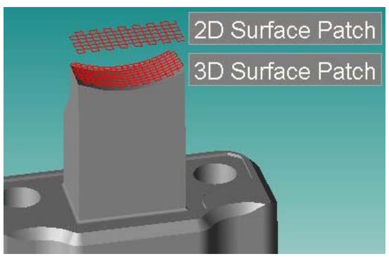


Figure.9 Surface patching zigzag toolpath for a curved surface

Toolpath Generation for Complicated Geometry

Concerning toolpath generation methods, one more issue was studied in this paper, which is the toolpath generation strategy for complicated geometries. For certain complicated shapes that include at least one inner loop or concave vertex, in order to avoid crossing the loops, the geometry must be divided into several sub-regions, among which any one has no inner loops or a concave vertex. Then every sub-region will become the target area, and the same toolpath generation method is used as discussed above to obtain reasonable toolpath separately. Here the cell decomposition algorithm is adapted to divide the target area into different sub-regions which are then filled by a certain toolpath pattern [25-26]. In Figure 10, the adaptive zigzag toolpath pattern is used to fill every sub-region as an example. After the target area is broken into sub-regions, the certain toolpath generation algorithm is used for every sub-region, and the boundary for every sub-region needs to be traveled before filling it with the zigzag toolpath to guarantee the features of the inner loops. Finally, the total toolpath for the complicated geometry divided into some sub-components is the summation of the toolpath for every single sub-region. Concerning the connection toolpath among all the sub-regions, the rapid travel lines are applied to realize the transition from one sub-region to the next.

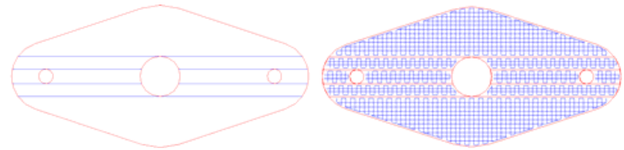


Figure.10 Complicated geometry filled by the interlaced zigzag toolpath

3. EXPERIMENTS

The repairing strategies discussed above have been applied on the mold/die repair for Spartan Light Metal LLC. Figure 11 shows the damaged die core before repairing and after deposition by the surface patching strategy after the damage was identified as worn-out surfaces. The top portion of the die is damaged and all the surrounding worn-out surfaces need to be repaired. Here the surface patching pattern was used to generate the adaptive zigzag toolpath to finish repairing all the surrounding damaged surfaces in an automatic mode without human interference. The whole repair job was finished in one setup, and the reliability of the repair job was greatly improved. The laser used was a NUVONYX 1K max diode laser. The laser processing parameters for cladding steel H13 powder were 600W with a stand-off distance from the nozzle to the top of the clad of 0.5 inch. The powder feed rate for H13 powder was 6g/min. The NC code was set to move the nozzle up 0.02 inch after each layer which is the layer thickness mentioned before. The travel speed of the nozzle was 20 inches/minute, and the track width was 0.05 inch.

(a) (b) (c)

Figure.11 Die core repaired via surface patching (a) Before repairing (b) After deposition(c) After surface machining

Figure 12 shows three moments of repairing three different damaged surfaces respectively. The whole repair job took less than 10 minutes except for the time for setting up the part. This proves that the surfacing patching method is much more effective compared with the feature replacing method for repairing corroded or worn-out surfaces. The surface patching method is an effective strategy to repair the usual kinds of damages in the die industry with high reliability.

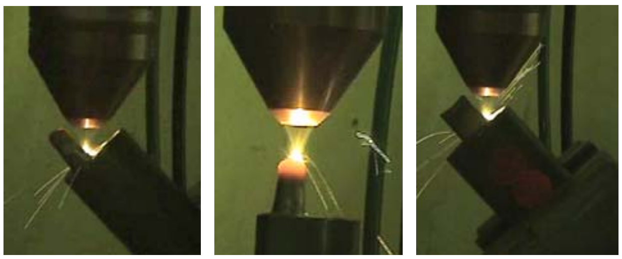


Figure.12 Automatic repairing processes

4. DISCUSSION

The interfacial strength is determined from a four-point bend test, as shown in Figure 13. The four-point flexture test is based on the storage of elastic energy on bending. Interfacial cracks propagate when the strain energy release rate equals to the critical energy release rate (G_c) of the interfacial failure. Four-point bend test has been used to analyze the interface between the substrate and the cladding produced by laser processing.

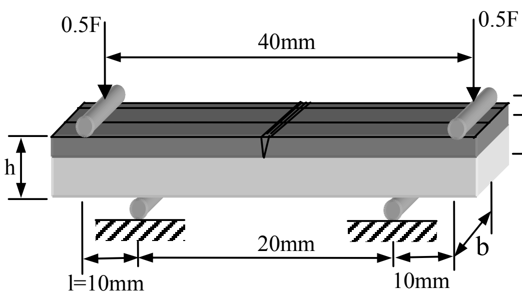


Figure.13 Bending test setup

Ashcroft et al. calculated the critical energy release rate (interfacial energy) for thick claddings [27]. Several critical parameters have been added into the calculation such as the thickness of the substrate, width of the substrate, and the thickness of the cladding itself as shown below.

$$G_c = (18 \cdot E_f \cdot d \cdot F^2 \cdot l^2 / b^2 \cdot T^6 \cdot E_s{}^2)(T^2 + d^2 / 3) \quad (6)$$

Where

E_f = Modulus of elasticity of the cladding;

d = Thickness of the cladding;

F = Critical load corresponding to de-lamination;

l = Distance between the inner and outer rollers;

b = Width of the substrate;

T = Thickness of the substrate; and

E_s = Modulus of elasticity of the substrate.

The 50 x 6 x 1 mm specimens are cut out from the deposition. A center pre-crack is made on the specimen in order to induce symmetrical cracks along the clad-substrate interface. The specimen is then loaded in a four-point flexture on an Instron TT-B Universal Testing machine until a new crack propagates through the entire cladding. The interfacial fracture energy of the laser cladding tool steel specimen is compared to the tool steel weld specimen of the exact same dimensions. The results show that the bond strength of the repaired part done in hybrid manufacturing systems is higher than that of the welding process.

In addition, another very important mechanical property for mold/die repair is thermal conductivity. By making electrical resistance measurements, thermal conductivity measurements can be made. The test results in Figure 14 show that the deposition repair has better thermal conductivity. Furthermore, the most practical evaluation is to test the repaired part in the real engineering environment. Also the above repaired die has been tested by Spartan Light Metal LLC and the result is very satisfying.

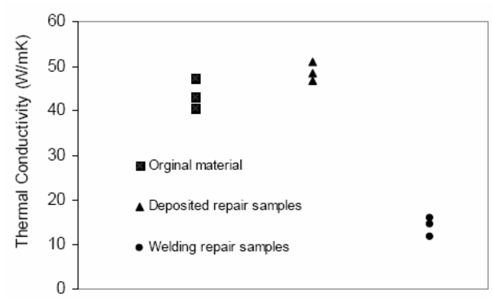


Figure.14 Thermal conductivity comparisons

5. CONCLUSIONS

This study shows that parts with different types of defects can be repaired in hybrid manufacturing systems by using either the feature replacement method or surface patching method. Accuracy and reliability can be achieved with the integration of the hardware and software automatically without human intervention. The bond strength and the thermal conductivity of the repaired part done in hybrid manufacturing systems are better than those of the welding process. Thus, hybrid manufacturing systems have the potential to repair damaged parts. For the complicated geometry divided into sub-components, the deposition sequence among all the sub-components is another research issue. In this paper, the transition among all the components is traveled rapidly. The optimized sequence will definitely enhance the deposition quality.

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